Microstructured optical fibres:
a novel tool to make light interact with gas efficiently

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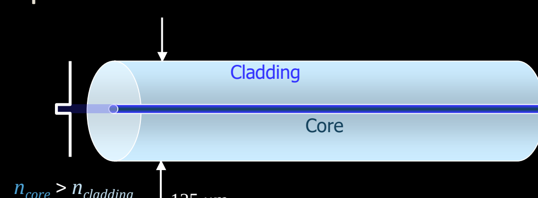
Group for Fibre Optics

At the origin, there is the optical fibre…



- **Fibres are small and can be seamlessly integrated in a structure and the environment**
- **Fibres are chemically inert and electrically insulating**
- **Fibres are extremely transparent (50% light remaining after 15km)**
- **Fibres do not distort signals (1 THz over 1000km)**
- **Fibres are green: they are made from a very abundant and widespread raw material: silica**

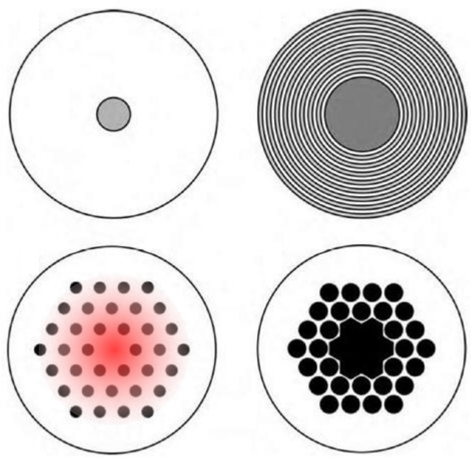
Different types of guiding have emerged

Index guiding

Antiresonant guiding

Effective index guiding

Photonic bandgap guiding



- Zero dispersion in the visible
  ➔ Supercontinuum generation
- Endlessly single mode fibres
- Small mode area
  ➔ Enhanced nonlinearities
- Large mode area
  ➔ Decreased nonlinearities
- Guiding in air, fluids and vacuum
  ➔ Absence of dispersion
  ➔ Absence of nonlinearities
  ➔ Interaction in gases & liquids
- Prospect to overcome the loss floor of silica

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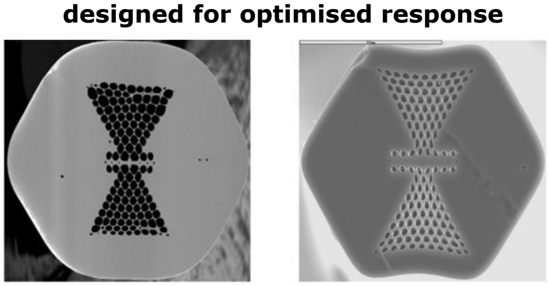
Fibres dedicated to pressure sensing

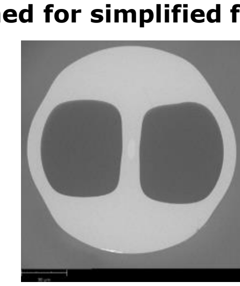
The isotropic hydrostatic pressure causes an asymmetric deformation of a fibre designed with an anisotropic profile ➔ **Birefringence is modified by pressure**

Photonic crystal fibre designed for optimised response



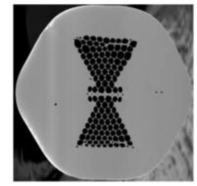
- ➢ Strong response
- ➢ High loss
- ➢ Poor uniformity
- ➢ High cost

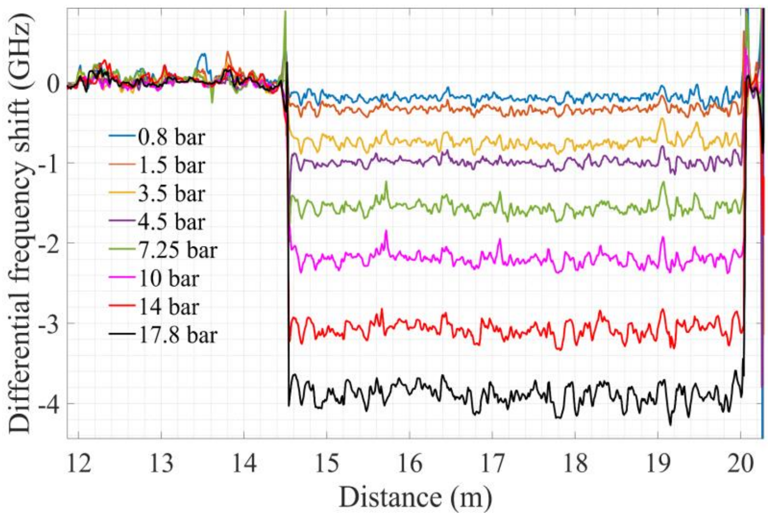
Side-hole fibre designed for simplified fabrication



- ➢ Good response
- ➢ Low loss
- ➢ Good uniformity
- ➢ Low cost

Distributed birefringence change vs Pressure





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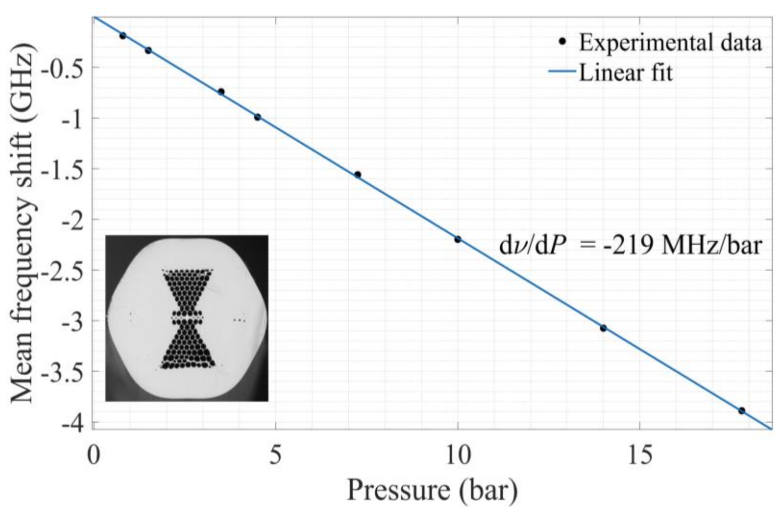
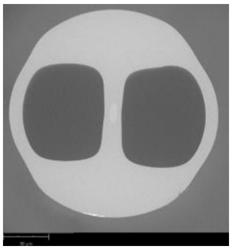
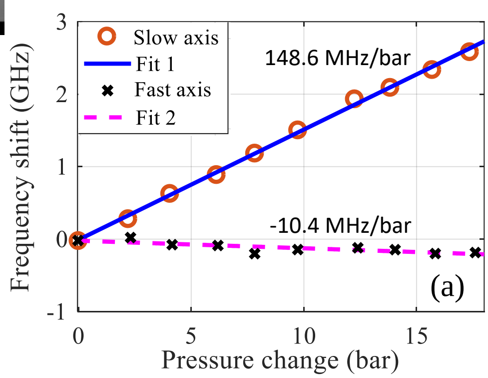
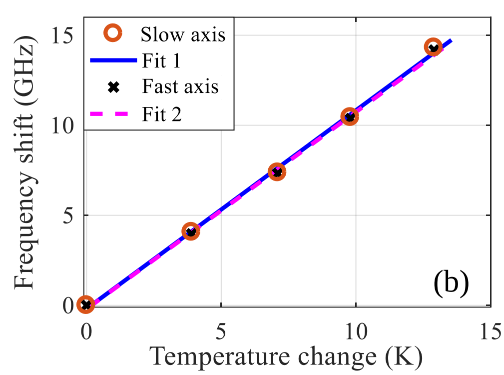


Pressure and temperature response along the 2 polarisations







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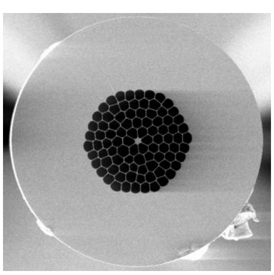
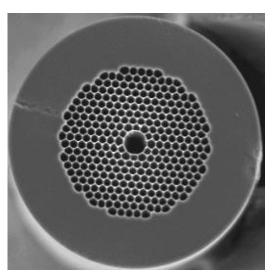
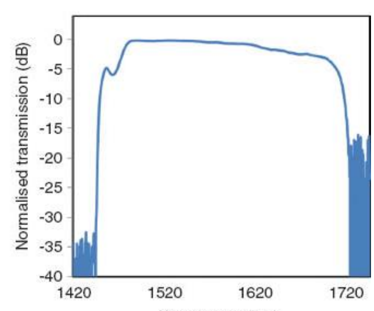
Index Guiding vs Photonic Bandgap Guiding







Light is essentially in SiO_2

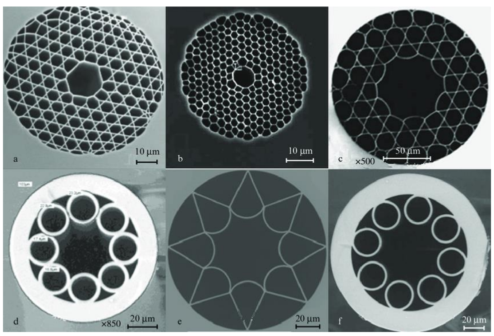
Light is essentially in air

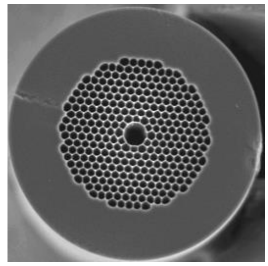
A tiny fraction propagates in SiO_2 (~1%)

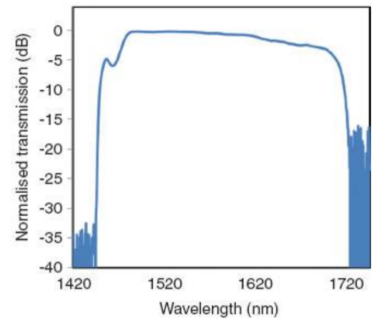
Loss limited by surface roughness

Index Guiding vs Photonic Bandgap Guiding

Structures have evolved to decrease the fraction of light in SiO_2







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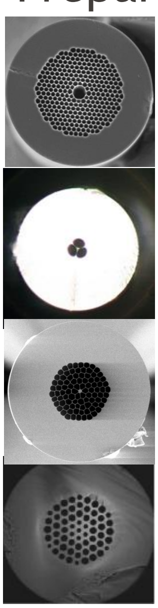
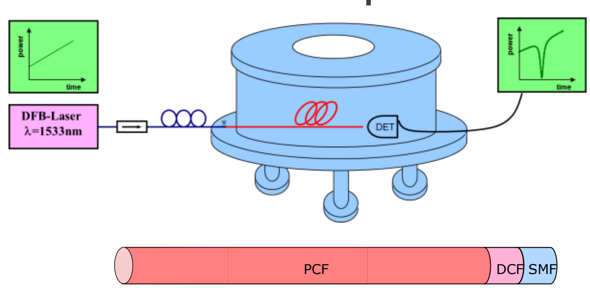
A tiny fraction propagates in SiO_2 (~1%)

Loss limited by surface roughness

Preparation of all-fibre absorption cells





The arc-fusion splice requires splicing at atmospheric pressure, but this means that the low-pressure gas inside the PCF will be contaminated by air.

The solution is to use the high permeability of helium through silica: we insert high-pressure (~ 2 bar) helium before making the splice. Helium will diffuse out of the silica walls in 1-2 hours.

P. S. Light, F. Couny, and F. Benabid, "Low optical insertion-loss and vacuum-pressure all-fiber acetylene cell based on hollow-core photonic crystal fiber," Opt. Lett. **31**, 2538-2540 (2006)

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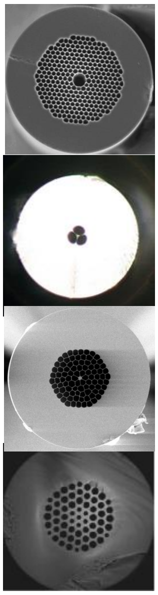

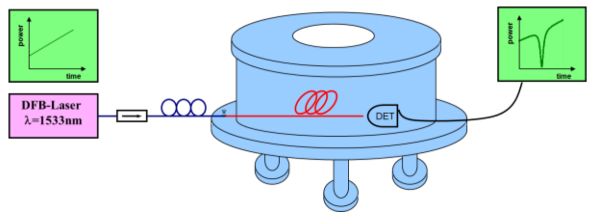

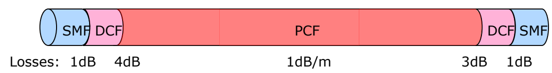

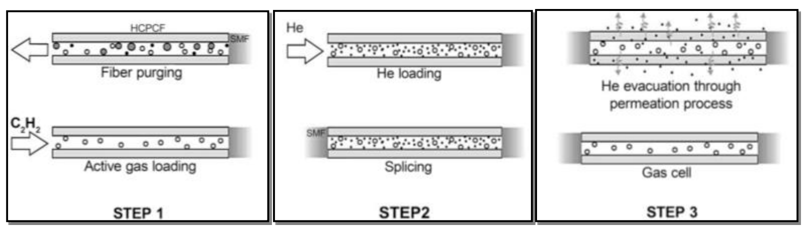

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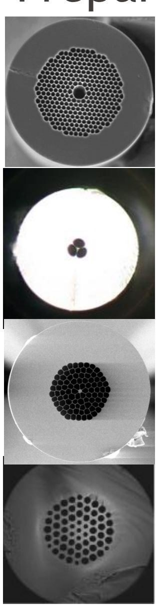

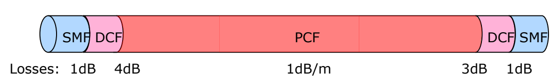

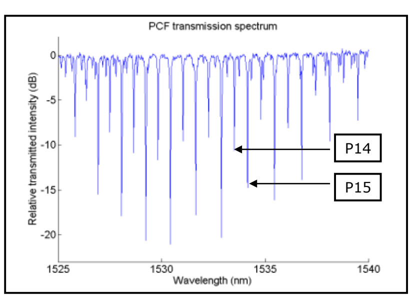

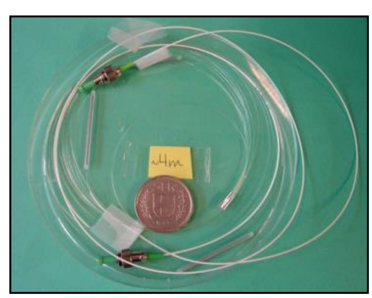

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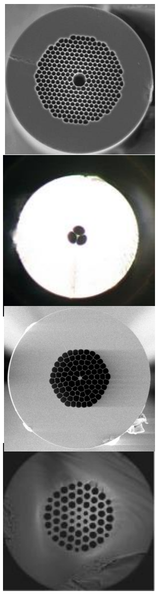
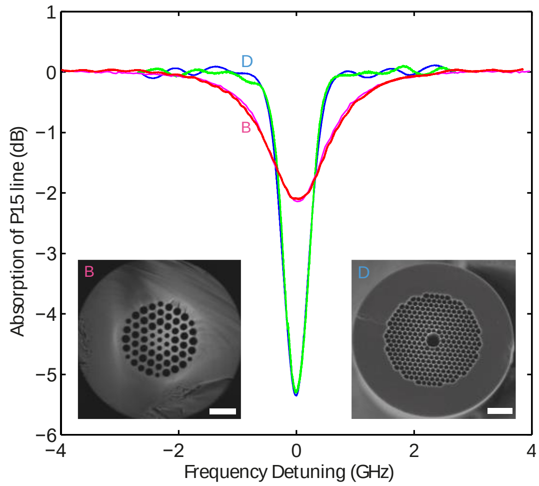
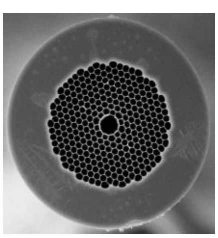


Long term response: Nov. 2008 – Sep. 2011

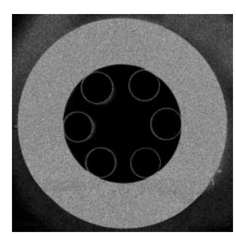


Clear interest for opto-acoustic interactions in gases



Hollow core fibres have a transparent and bright future:

- Will probably outperform silica fibres in term of loss (currently < 1 dB/km)
- Higher power handling capability (no nonlinear effect)
- No dispersion, broader spectral range
- Low latency



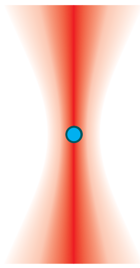
➔ **The possibilities for optical signal processing are much limited, accordingly!**

If **stimulated Brillouin scattering** could be activated in gas
➔ a wide choice of all-optical interactions could be implemented:

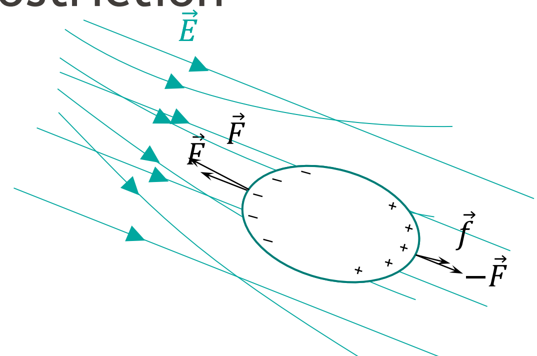
- Amplification & lasing
- Slow & fast light
- Selective spectral filtering
- Optical storage
- All-optical calculus
- Distributed sensing, etc…

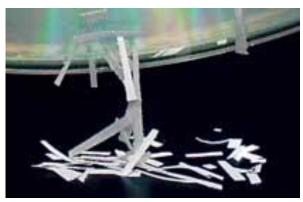
If observable, will the interaction be large enough to offer any interest?

Polarisation force & Electrostriction



Optical trapping & tweezers
Nobel Prize 2018



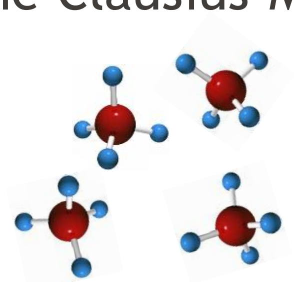


A dielectric object in a non-uniform field feels a force toward regions of higher field strength.

$$\vec{F} \sim \vec{E} \;\; \vec{\nabla} \;\; \vec{E}$$

Induced charges — Non-uniformity strength — Force strength

The Clausius-Mossotti relation - Elasto-optic effect



$$\frac{n^2-1}{n^2+2} = N_A \frac{\alpha}{3M}\rho$$

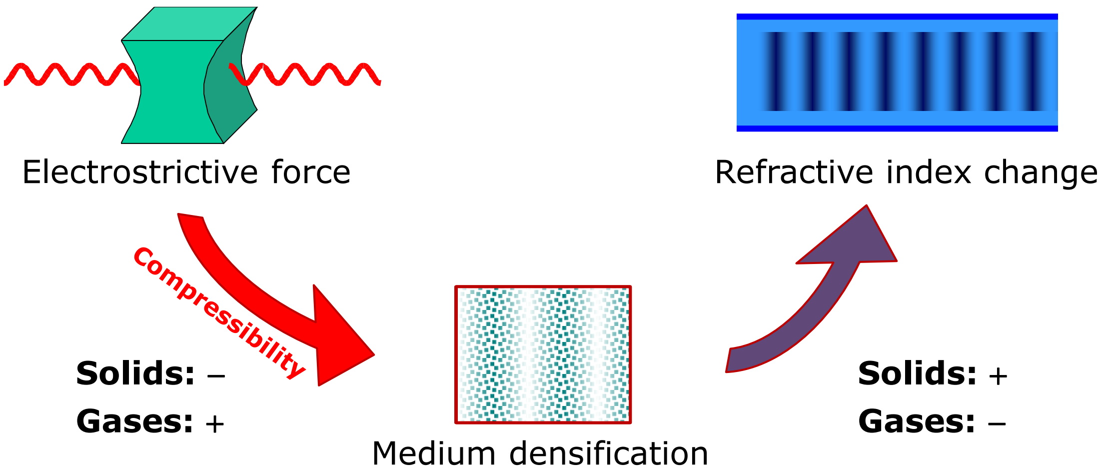
with

- ρ : Material density
- N_A : Avogadro's constant
- α : Molecular polarisability
- M : Molar mass

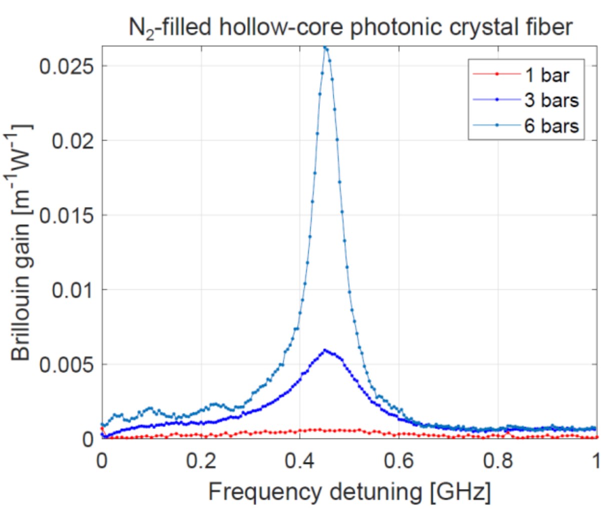
For a tenuous medium like a gas ($n \sim 1$) : $$n \approx 1 + N_A \frac{\alpha}{2M}\rho$$ ➔ $$\Delta n \approx N_A \frac{\alpha}{2M}\Delta\rho$$

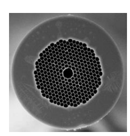
A large **density change** leads to a proportionally large **change in refractive index**

From electrostriction to dynamic grating

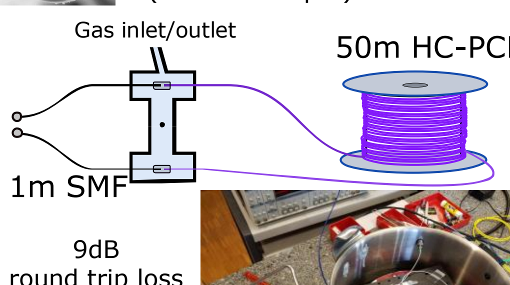


Observation of stimulated Brillouin scattering in gas





All results were obtained in a 50 metre gas-filled hollow-core photonic bandgap fibre (core size 10µm)



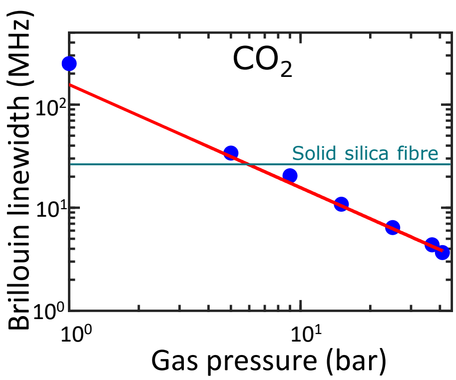
Brillouin linear gain in silica fibres is 100X larger!

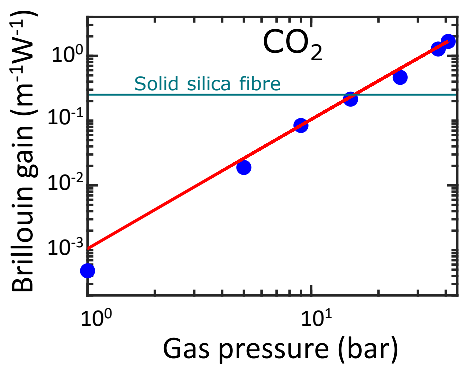
Pressure dependence

Opto-acoustic strength depends linearly on pressure: $\Delta n \approx N_A \dfrac{\alpha}{2M} \Delta\rho \sim P$

Acoustic lifetime also depends linearly on pressure: $\tau_A \sim P$ ➔ **Gain** $g_B \sim P^2$

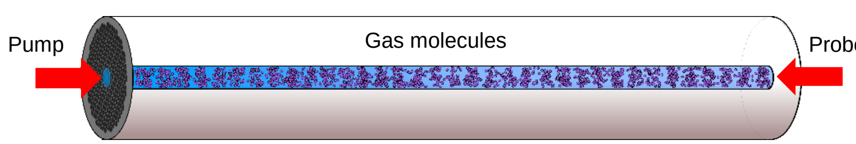
Pressure squared!



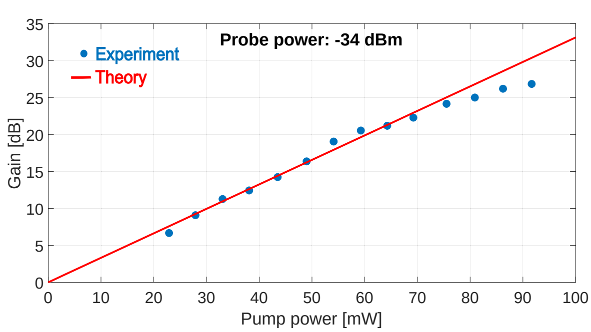


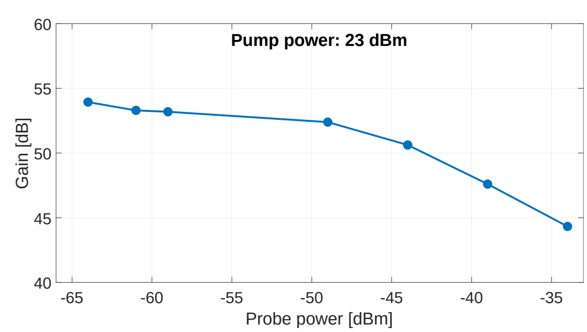
A hollow-core fibre can sustain a pressure up to 1000 bar and more.

Amplification

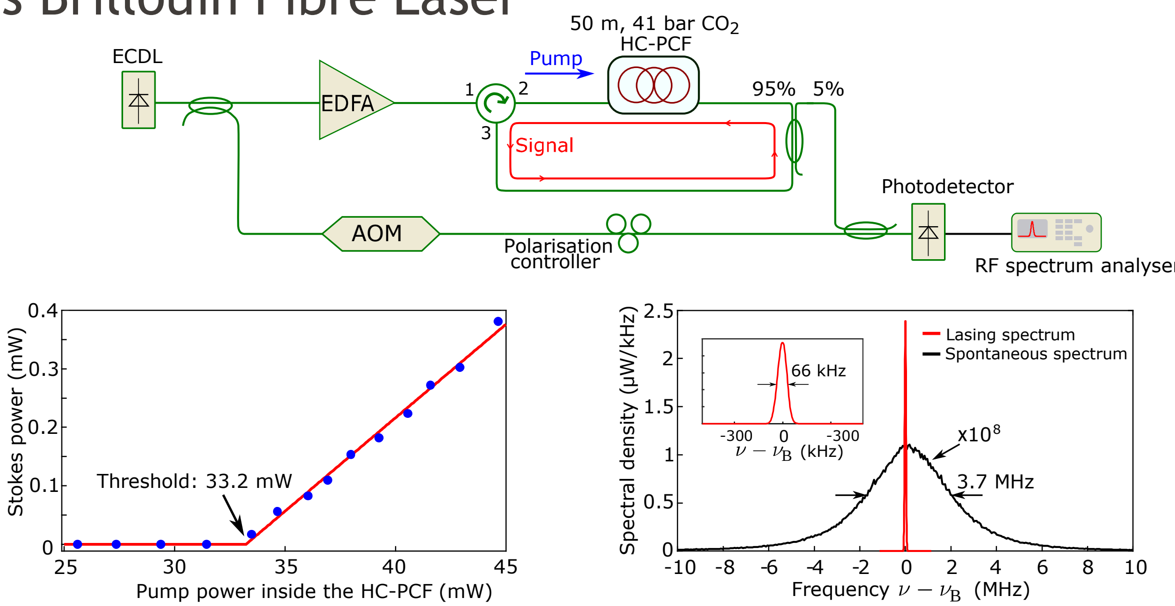


Gain obtained along a 50m hollow-core fibre filled by CO_2 at 41 bar





Gas Brillouin Fibre Laser



Influence of the gas species

The Brillouin gain depends on several material parameters:

- Molecular mass ↗
- Molecular size ↗
- Viscosity ↘
- Polarisability ↗

Gas	Name	V_a[m/s]	m[g/mol]	d[pm]	$\eta_s[10^{-5}\mathrm{Pa}\cdot\mathrm{s}]$
CH_4	Methane	466	16	400	1.88
N_2	Nitrogen	354	28	370	2.86
CO_2	Carbon dioxide	280	44	232	2.71

Measured Brillouin gains at 24°C and 10 bar:

Gas	Name	ν_B[MHz]	$\Delta\nu_B$[MHz]	$G[m^{-1}W^{-1}]$
N_2	Nitrogen	451	41	0.025
CH_4	Methane	580	40	0.034
CO_2	Carbon dioxide	351	21	0.105

At first glance, gases with complex and heavy molecules should deliver more gain.

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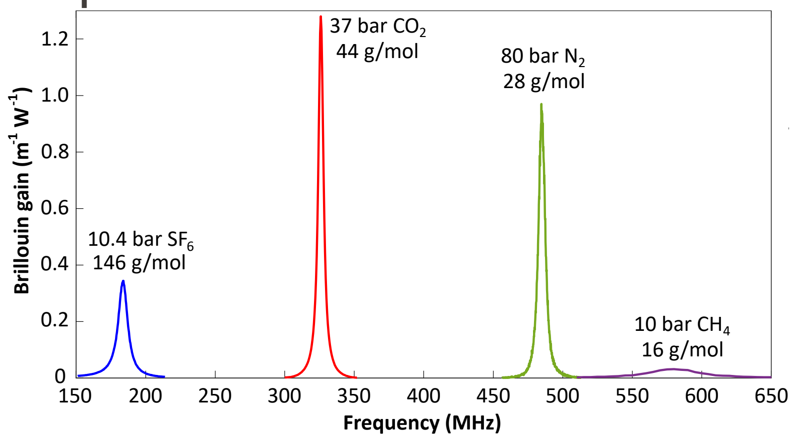


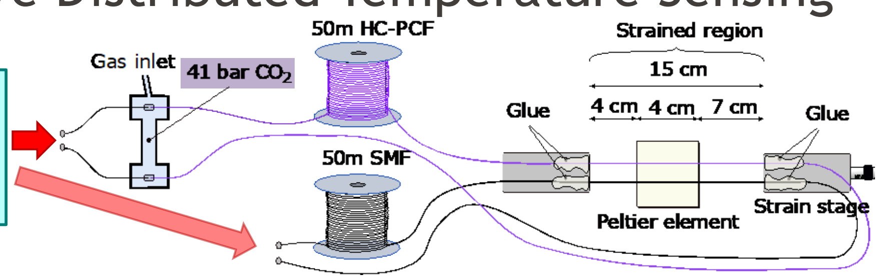
At first glance, gases with complex and heavy molecules should deliver more gain.

But:
- May quickly turn into **liquid phase** at higher pressure.
- May show **spectral absorption lines**, moreover significantly broadened at high pressure

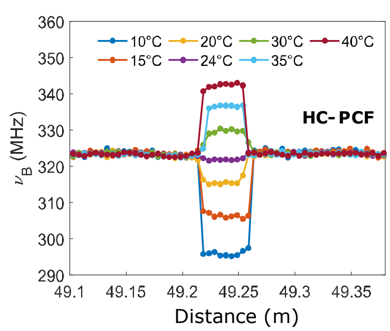
Strain-Insensitive Distributed Temperature Sensing

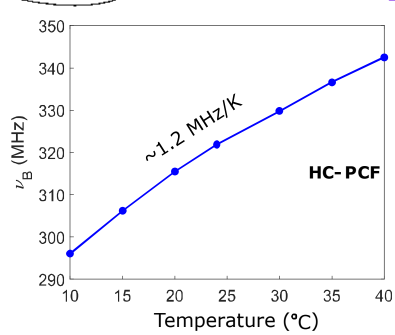
Pseudo-random phase-coded Brillouin correlation-domain analyser (Spatial resolution ~1-2 cm)

A. Zadok et al
Random-access distributed fiber sensing
Laser & Photonics Reviews **6**, L1–L5 (2012).



No strain





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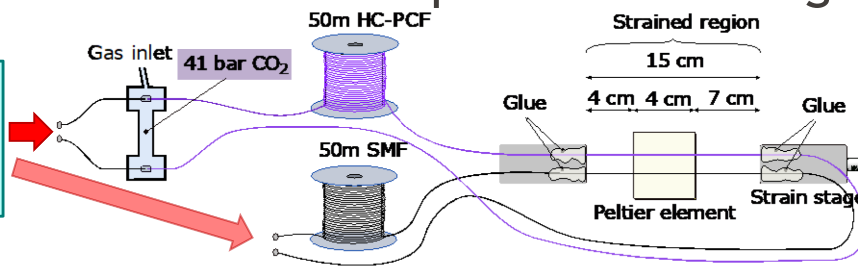
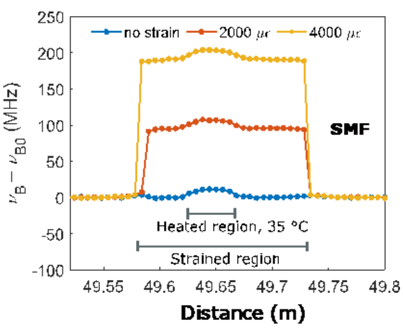
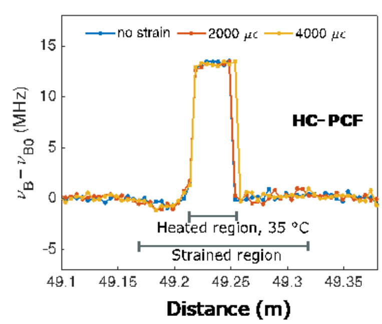


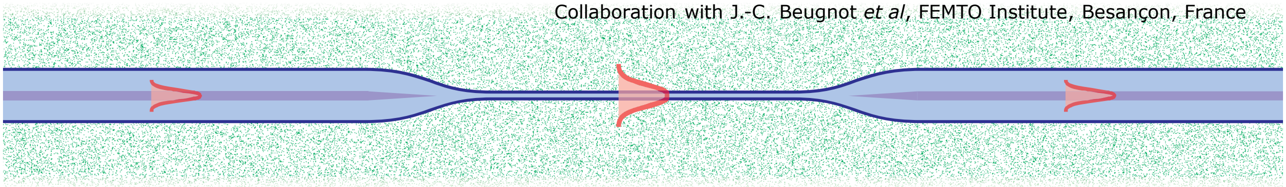
With strain

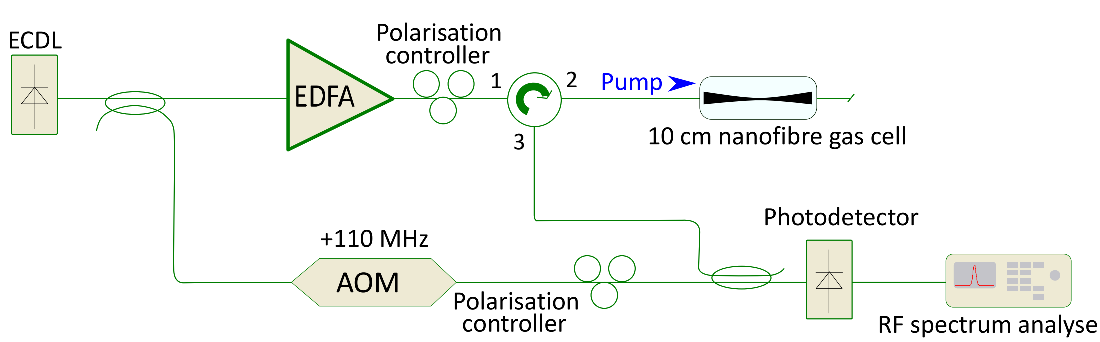




Brillouin amplification using evanescent field in gas

Collaboration with J.-C. Beugnot *et al*, FEMTO Institute, Besançon, France





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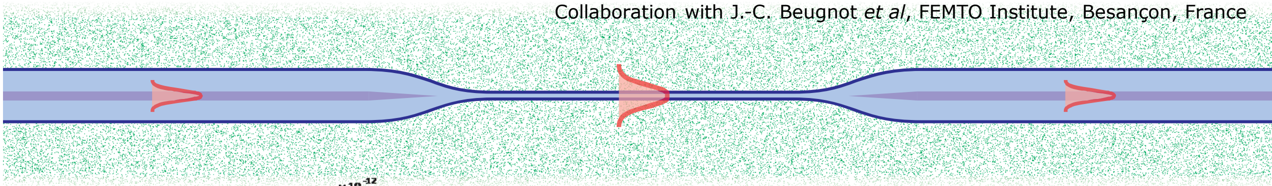
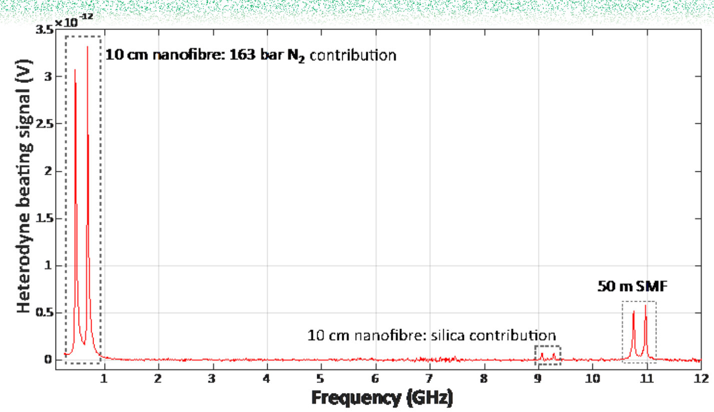
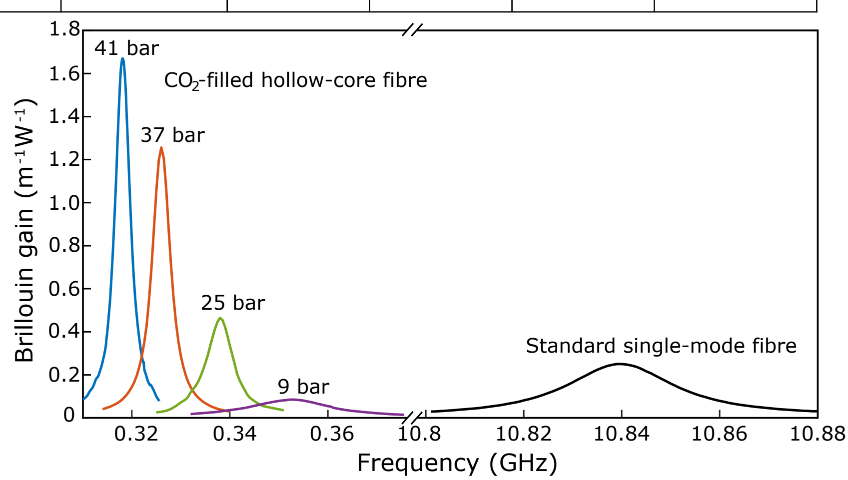




Final words

	SBS in silica	SBS in chalcogenide	Raman gain in H_2 at 10 bar	Forward Brillouin gain in air	SBS in N_2 at 1 bar	SBS in N_2 at 1000 bars
Linear gain (m/W)	3×10^{-11}	6×10^{-9}	4.2×10^{-12}	4×10^{-14}	3×10^{-14}	3×10^{-8}

Stimulated Brillouin scattering in gases can outperform any existing nonlinear amplification!



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